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Ventilation Efficiencies of Desk-Mounted Task/Ambient Conditioning Systems

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Abstract
In laboratory experiments, we investigated two task/ambient conditioning systems with air supplied from desk-mounted air outlets to efficiently ventilate the breathing zone of heated manikins seated at desks. In most experiments, the task conditioning systems provided outside air while a conventional ventilation system provided additional space cooling but no outside air. Air change effectiveness (i.e., exhaust air age divided by age of air at the manikin's face) was measured with a tracer gas step-up procedure. Other tracer gases simulated the release of pollutants from nearby occupants and from the floor covering, and the associated pollutant removal efficiencies (i.e., exhaust air concentrations divided by concentrations at manikin's face) were calculated. High values of air change effectiveness (~ 1.3 to 1.9) and high values of pollutant removal efficiency (~ 1.2 to 1.6) were measured when these task conditioning systems supplied 100% outdoor air at a flow rate of 7 to 9 L s^{-1} per occupant. Air change effectiveness was reasonably well correlated with the pollutant removal efficiency. Overall, the experimental data suggest that these task/ambient conditioning systems can be used to improve ventilation and air quality or to save energy while maintaining a typical level of IAQ at the breathing zone.
Key words: Task/Ambient conditioning; Air change effectiveness; Pollutant removal efficiency; Ventilation; Indoor air quality

Introduction

A field study indicated that a larger than expected percentage of office workers were not satisfied with their thermal environment while at work, even though ASHRAE Std 55 (ANSI/ASHRAE, 1992) thermal comfort conditions were met (Schiller et al. 1988). Variations in thermal preferences, clothing, and activity levels are one source of thermal discomfort. While some workers prefer to be cooler, other workers in nearby workstations prefer to be warmer. Since a single uniform thermal environment will not satisfy all workers, some manufacturers and researchers have postulated that giving workers control of thermal conditions at their workstation will increase thermal comfort and possibly increase worker productivity. Task/ambient conditioning (TAC) is a method for providing occupants with control of a local supply of air so that they can adjust their individual thermal environment. Controlled variables could be the supply-air temperature, velocity, direction, the ratio of room air to main air handling system supply air, and the radiant temperature. TAC systems may provide all or part of the conditioned air to the occupied space.

TAC systems also have the potential to improve ventilation at the occupant's breathing zone because they can provide supply air preferentially toward the breathing zone. Supply air from TAC systems usually contain a high percentage of outside air, which generally does not contain a high concentration of indoor-generated pollutants. The air supply outlets of current TAC systems are located at the floor, mounted on the desk, or incorporated within the workstation partitions.

Previous research concerning TAC systems has shown that it is possible to improve ventilation at the breathing zone (relative to ventilation with perfect mixing) using TAC systems with desk-mounted (Faulkner et al. 1993) or floor-mounted (Fisk et al. 1991 and Faulkner et al. 1995) air supply outlets. However, the degree of enhancement has been generally small (~20% - 40%) and observed primarily during operating conditions that are likely to be uncomfortable because of high air velocities.

In this paper, to characterize the improvement in ventilation at the breathing zone we use two "ventilation efficiency" parameters. The first is the air change effectiveness (ACE), defined as the age of air that would occur throughout the room if the air was perfectly mixed, divided by the average age of air where occupants breathe (ASHRAE, 1997). The age of air at a particular location is the average time elapsed since molecules of air at that location entered the building. Because the average age of air exiting the room is identical to the age of air that would occur throughout the room if the indoor air were perfectly mixed (Sandberg and Sjoberg 1983), the ACE is also the exhaust-air age divided by the average age of air where occupants breathe. A short-circuiting flow pattern increases the room-air age and causes ACE to be less than unity. Perfect mixing results in an ACE of unity. Preferentially ventilating the breathing zone with outside air will cause the ACE to be greater than unity.

The second ventilation efficiency parameter is the pollutant removal efficiency (PRE). Although rarely used, the PRE is a more direct indicator than ACE of the effectiveness of the ventilation process in controlling occupants' exposures to indoor-generated air pollutants. We define the PRE as the time-average concentration of pollutants in the exhaust air divided by the time-average concentration where occupants breathe. The PRE is a function of the locations of pollutant sources and the nature of the pollutant emission process, e.g., emitted with or without momentum. PREs also depend on the indoor airflow pattern and local sinks. If the pollutant sources are distributed uniformly in a space and the pollutant is emitted without momentum, then we expect the values of PRE to be correlated (not necessarily identical) with the values of ACE.

Prior research has shown not only improved ventilation efficiency while using TAC systems, but also increased thermal comfort and occupant satisfaction (Bauman and Arens 1996, Bauman et al. 1998). In addition, energy savings may be realized using TAC systems if they use occupancy sensors to turn off the systems when workstations are unoccupied. The savings realized from the use of occupancy sensors will depend upon the amount of time the workstation is unoccupied. Energy savings may also be realized while the building is operating in a cooling mode by maintaining temperatures away from the workstations warmer than temperatures at the workstations (Borgers and Bauman 1994). Another potential benefit to using TAC systems is the cost savings associated with improved worker productivity and reduced sick leave (Seem and Braun 1992).

Research Objectives
The objectives of this research were to determine the ACE and the PREs obtained through the use of two desk-mounted TAC systems operating in conjunction with a conventional (ceiling supply and return) heating ventilation and air conditioning (HVAC) system.

Task/Ambient Conditioning Systems
The first TAC system evaluated is the Personal Environmental Module (PEM) manufactured by Johnson Controls Inc. The PEM contains a thermally and acoustically insulated mixing box that encloses fans, dampers, and electronic controls. The dampers control the percentages of recirculated room air and ventilation system supply air (thus controlling the temperature of air supplied). This mixing box is installed underneath a desk. Air is supplied to the mixing box from a dedicated air-handling unit (AHU) via a flexible duct that is connected directly to supply ducts or to an under-floor supply air plenum. Another stream of air enters the mixing box through an air inlet beneath the desk. After passing through the mixing box, the mixture of AHU supply air and room air exits through two desk-top-mounted air supply outlets located at the back corners of the desk. The PEM has a control panel from which the following parameters can be changed: air flow rate, percent of room air that is mixed in the mixing box with air from the main AHU, volume of a white noise generator, dimming of a task light, and power to a radiant heating panel. The air supply outlets on top of the desk can be rotated 360° in the horizontal direction and contain movable vanes which can be rotated ± 30° in the vertical direction. The normal range of supply air flow from the PEM is 6 to 71 L/s, although most of our tests utilized supply flow rates at the lower end of this range.

The second TAC system is the Climadesk manufactured in Sweden by Mikroklimat. The Climadesk includes a panel attached to the underside of a conventional desk, connected by a flexible duct to a portable fan-filter unit placed next to the desk. The fan-filter unit is supplied with air from the same dedicated AHU as the PEM. Supply air exits two adjustable outlets underneath and close to the underside of the worksurface. These outlets are located close to a seated worker's knees and direct air horizontally above the seated worker's thighs and towards the torso. In the horizontal plane, the angle of air supply from these outlets is manually adjustable. There is an additional, non-adjustable outlet at the front edge of the desk, which directs air almost vertically upwards, but slightly away from a seated worker, to minimize unwanted cooling of the torso. A variable proportion of the total air flow (0-100%) can be directed to this third outlet, as desired by the occupant. All three outlets are fitted with metal "honeycomb" final sections whose purpose is to induce parallel flow and reduce entrainment of the vertical jet. The maximum primary airflow from the Climadesk is 7 L/s. A controllable radiant heating panel, attached to the underside of the desk, can provide heating of the lower part of the body.

Research Methods

All experiments were performed in a controlled environment chamber (CEC) with a 5.5 m by 5.5 m floor and 2.5 m high ceiling. The CEC resembles a modern office space and has provisions for a high degree of control over the method of ventilation and the indoor thermal environment (Bauman and Arens 1988). Figure 1 shows the floor plan of the workstations in the chamber. During experiments, two identical TAC systems were operated, one in workstation 2 (WS2) and one in WS3, while a conventional HVAC system supplied air through a perforated diffuser located in the ceiling. Air was exhausted from the chamber through a ducted ceiling-level return grill. All measurements were performed under steady state conditions.

The furnished chamber contained sources of heat and air motion typical of real offices, including: overhead lights (with a total power of 500 W of which roughly 100 W directly entered the chamber); and a personal computer containing a small cooling fan and a monitor in each workstation (90 W each). A seated heated manikin was located in both WS2 and WS3 with both of the TAC systems. Electric resistance heating elements wrapped around the manikin in WS 3 released 75 W (a typical rate of release of sensible heat by an office worker). The other skin-temperature-controlled thermal manikin in WS2 released approximately 100 W. For experimental purposes, each workstation contained a 15 W particle counter.

Experimental Conditions

The test variables are listed in Table 1. The test conditions were based upon previous tests with TAC systems and anticipated use of these systems. Each workstation with the TAC system and manikin were configured identically for each test. With the PEM operating, the air supply outlets were either pointed toward the occupant or parallel to the side walls of the workstation see Figure 2. With the Climadesk operating the supply air was either supplied horizontally under the desk (parallel to the seated manikin's thighs), see Figure 3, vertically upward from the front edge of the desk, see Figure 4, or an approximately equal air flow in both the horizontal and vertical directions. The total amount of outside air supplied to the room, nominally 10 L/s-occupant, was based upon ASHRAE Standard 62 (ASHRAE, 1989). During all but three tests, all of the outside air was supplied to the room through either the PEM or Climadesk. The conventional overhead ventilation system recirculated air between 61 - 71 L/s (which is less than the typical overhead supply flow rate for a room of this size). In three tests with the PEMs operating, some room air was mixed with outside air that was supplied through the desktop air outlets. For most tests the air was supplied through the TAC systems at nominally 19 °C (except for three tests in which it was 25 °C). The room temperature was controlled at ~25 °C. Both the supply air temperature and the room temperature are higher than typically found in a conventionally ventilated office space because the TAC systems provide local cooling. In all but four of the tests, the manikins were seated upright with their faces located about 15 cm back from the edges of the desks. Four tests were run with the manikins leaning slightly forward with their faces in the vertical air supply jets emerging from the Climadesks.

Measurement Methods

Air Change Effectiveness

ACE was measured using a tracer-gas step-up procedure. After steady state test conditions were established, sulfur hexafluoride (SF_6) tracer gas was injected at a constant rate (within 1%) into the supply or outside air duct. Mixing fans inside the HVAC system ductwork ensured thorough mixing of the tracer in the supply airstream.

Using three gas chromatographs with electron capture detectors (GC-ECD), tracer-gas concentrations were measured as a function of time during the period of concentration increase. Concentrations were measured approximately every four minutes at the following locations: the outside air duct; the supply air duct; the return/exhaust duct; and seven locations within the chamber (at the mouth/nose in each workstation and in WS2, 15 cm in front of the nose and immediately above each shoulder). The GC-ECD units were calibrated after each test with thirteen calibration gases.

Ages of air (τ) were determined from the SF_6 tracer data via the equation

$$\tau = \frac{1}{C(t_{end})} \int_0^{t_{end}} [C(t_{end}) - C(t)]dt \qquad (1)$$

where C(t) is the tracer-gas concentration at the point in question, $C(t_{end})$ is the steady-state concentration at the end of the step-up, and t is the time elapsed since the start of tracer-gas injection. The ACE was determined from:

$$ACE = \frac{\tau_{return}}{\bar{\tau}_{bl}} \qquad (2)$$

where τ_{return} is the age of the return/exhaust air and $\bar{\tau}_{bl}$ is the average age of air at the two occupied breathing level measurement locations.

Pollutant Removal Efficiency

For the measurements of PRE, three different perfluorocarbon tracer-gases were used to simulate sources of indoor-generated pollutants. To simulate emissions from the floor covering, four passive emitters of metaperfluorodimethylcyclohexane (C_8F_{16}) tracer gas were placed on the floor, one in each workstation. To simulate emissions from occupants, two emitters of perfluorodimethylcyclobutane (C_6F_{12}) tracer gas were attached to the manikin in WS2 and two emitters of perfluoromethylcyclohexane (C_7F_{14}) tracer gas were attached to the manikin in WS3. The emitters on the manikins were located near the armpits to simulate the emissions of body odors by occupants. All emitters were placed in the room the day before the test so that concentrations would reach steady state before the start of the test. To measure the average concentrations of the perfluorocarbon tracer gases, air samples were drawn from the occupants' breathing zone and the return/exhaust duct at a constant rate with peristaltic pumps and stored in 2-liter sample bags. The samples were collected for approximately the same time periods as the tracer step-ups. The bags were subsequently analyzed with a gas chromatograph (GC with electron capture detector). The tracer emitters and analytical system have been described previously (Fisk et al. 1993; Faulkner et al. 1999)

The PRE for the "Floor" and "Body" pollutants were calculated from the equations:

$$PRE_{Floor} = \frac{C_{Floor}^{Return}}{\frac{1}{2}\left(C_{Floor}^{BL2} + C_{Floor}^{BL3}\right)} \tag{3}$$

$$PRE_{Body} = \frac{1}{2}\left(\frac{C_{Body2}^{Return}}{C_{Body2}^{BL3}} + \frac{C_{Body3}^{Return}}{C_{Body3}^{BL2}}\right) \tag{4}$$

where the superscript denotes the measurement location (Return duct, Breathing Level in either WS2 or WS3) and the subscript denotes the location of the pollutant source (floor, manikin in WS2 or manikin in WS3). The values of PRE_{Body} indicate the efficiency of the ventilation process in controlling exposures to pollutants emitted by the occupants in the adjoining workstation.

Percentage of Outside Air and HVAC Air Flow Rates and Temperatures

To determine the percentage of outside air supplied either to the TAC system or to the main HVAC system, one of two methods was used. The first method was to measure the tracer gas concentrations in the return/exhaust airstream and the supply airstream downstream of the junction of the outside-air and supply-air ducts. The percentage of outside air was determined from the equation:

$$\%OA = (1- C_m/C_r)100\% \tag{5}$$

where C_m is the concentration of tracer gas in the mixture of outside and recirculated air and C_r is the concentration in the return/exhaust air.

To obtain nearly instantaneous values of the percentage of outside air, a second method was to use flowrate measurements of the outside airstream and the supply airstream made using Pitot tubes and pressure transducers. The percentage of outside air was determined from the equation:

$$\%OA = (Q_{OA}/Q_s)100\% \tag{6}$$

where Q_{OA} is the flowrate of the outside airstream and Q_s is the flowrate of the supply airstream.

The flow rates of air in the HVAC system were measured using Pitot tubes and Venturi flow meters with differential pressure transducers. The airstream temperatures were measured with thermistors. The measurement system is described in detail elsewhere (Arens et al. 1991, Fisk et al. 1991).

Results

Measurement precision

During Test 129W (see Table 1), the chamber air was mixed vigorously with fans which ideally should produce the same average concentration for each tracer at every point in the chamber. Consequently, all of the ages of air should be identical and all of the ratios of concentrations should equal unity. However, due to measurement imprecision and errors (and possible imperfect mixing despite the operation of mixing fans) not all of the measured ages of air and tracer gas concentrations are equal. Based on these results and the results of 11 previous "well-mixed" tests within the chamber, the estimated 95% confidence interval for ACE during well-mixed tests is 1.02 ± 0.06.

Since PRE has not been measured during previous "well-mixed" tests, we estimated the precision based upon measurements of all locations within the chamber during Test 129W. Using propagation of error analysis, we estimate the 95% confidence interval for PRE to be 0.95 ± 0.14 and 0.98 ± 0.14 for the floor and body respectively.

Air Change Effectiveness and Pollutant Removal Efficiencies

The ACEs and PREs measured during many of the experiments were high (1.3 to 1.9 for ACE; 1.2 to 1.6 for PRE_{Floor} and PRE_{Body}). Based upon the above analysis for the well-mixed tests, these results are statistically significant at the 95% confidence level. These results indicate that the TAC systems, relative to indoor air that is thoroughly mixed by other ventilation systems, can substantially increase the effective rate of ventilation at the breathing zones and reduce pollutant exposures.

The highest values of ACE and PRE were measured, with either of the TAC systems supplying 100% OA at approximately 7 - 10 L/s per occupant, with the air supply directed toward the manikin's face. These values occurred with the supply air temperature either 6 ^{o}C below room temperature or at room temperature. With the PEM, the nozzles were pointed toward the manikin's face and with the Climadesk, the manikin leaned into the vertical air jet exiting the front edge of the desk. In experiments with the Climadesk (Tests 141 - 144), the high values of ACE and PRE were very localized at the mouth and nose, as measurements of ACE and PRE 15 cm in front of the nose and mouth were close to unity. High values of ACE and PRE were not measured with the manikin seated upright and air supplied through the vertical outlet of the Climadesk (i.e., with the face not located directly in the vertical supply air jet) see Test 130.

The Climadesk system also produced high ACE and PRE values when the air supply was entirely horizontal (Tests 131 and 140), directed toward the manikin's torso from beneath the desk. Tests with a smoke tube suggest that some of the outside air supplied horizontally by the Climadesk was entrained in the thermal plume flowing upward along the body and carried into the region of the nose and mouth. Under these operating conditions, high values of ACE and PRE were maintained 15 cm in front of the nose and mouth.

With approximately equal amounts of air supplied vertically and horizontally from the Climadesk, the ACE and PRE values were not consistent. Results from Test 132 indicated little or no improvement in ACE or PRE. Whereas results from Test 145 indicate enhanced ACE and PRE as we had expected. Similar to configurations discussed above, the improved

ACE and PRE values with this configuration may be highly dependent upon the manikin position relative to the Climadesk outlets and the edge of the desk.

In two tests with the Climadesk, high values of ACE and PRE were maintained when approximately half of the total outside air supply was provided by the conventional overhead ventilation system. We anticipated a decrease in performance under these operating conditions. However, these results were obtained in tests with the manikin's head located directly in the vertical air supply jet. As discussed above, under these conditions the ACE and PRE will vary considerably with small changes in the position of the head and an optimal location of the manikin's head may have counteracted the expected performance decrease.

Figure 5 shows ACE vs PRE and a linear trendline for both the Floor and Body tracers. The values of ACE and PRE_{Floor} were reasonably well correlated (R = 0.92). The correlation of ACE with PRE_{Body} was weaker (R = 0.83). This strong correlation between ACE and PRE_{Floor} has been measured previously (Fisk et al. 1997). Since PREs, relative to ACEs, can be measured for a wider range of conditions, such as naturally ventilated buildings and buildings with non-steady air flow rates (Fisk et al. 1997, Faulkner et al. 1999), PRE measurements may turn out to be a practical substitute for more difficult ACE measurements.

Discussion and Conclusions

In our previous related research, the TAC systems supplied air at much higher flow rates. With air supplied from the PEM at flow rates of 19 to 94 L/s, PREs and ACEs were significantly above unity only if this air was 100% outside air directed toward the occupants face (Faulkner et al. 1993) – a condition that is not likely to be comfortable (Bauman et al. 1993). Directing the air away from the face made conditions more comfortable but resulted in ACEs and PREs close to unity. These results suggest that high rates of air supply from TAC systems may vigorously mix the air within the workstation, making it difficult to preferentially ventilate the breathing zone. With the lower TAC supply flow rates employed in this current set of experiments and the outlets pointed at the occupant, thermal comfort conditions were found generally acceptable (Tsuzuki et al.1999). One exception may be the maximum velocity measured (1.34 m/s) at the face of the manikin while its head leaned into the vertical jet of the Climadesk. Unwanted air movement of 1.34 m/s may be unacceptable by some thermal comfort standards. However, with TAC systems, users can choose what is acceptable for their own comfort.

Our prior research on TAC have also included experiments with air supplied from outlets mounted within the floor of the workstation (Fisk et al. 1991, Faulkner et al. 1995). ACEs were significantly above unity only when the air was directed in a manner that yielded an upward vertical displacement flow. However, commercially available displacement ventilation diffusers, which do not allow for individual control, may provide a superior option for obtaining a displacement flow pattern.

For the Climadesk unit operating with a vertical air supply jet, a superior ventilation performance was achieved with the occupant's head located precisely within the vertical jet of air. Since real occupants will maintain a variety of postures and locations, the ACEs and PREs achieved in practice may be much closer to unity. Our data and understanding of system performance suggest that supplying air horizontally is the more robust method of assuring high ventilation efficiencies. However, this expectation, based on results of only two experiments, needs to be confirmed through additional experiments, including some with real occupants.

Ideally, TAC systems should maintain high values of ACE and PRE while enabling occupants to adjust their local thermal environment and remain comfortable. Concurrent to our measurements, Tsuzuki et al. (1999) made measurements using the thermal manikin in WS2. With the Climadesk or PEM supplying 7 - 10 L/s, they measured a maximum effective whole body cooling equivalent to approximately 1 °C. Thus, these two TAC systems can measurably reduce the effective temperature and preferentially ventilate the breathing zone. Use of the radiant heaters integral to each TAC system increases the range of thermal control. However, if occupants reduce the rate of air supply or change the air supply direction to increase the effective temperature, ACEs and PREs are likely to differ from the values measured in these experiments. Reducing the air supply rate could conceivably increase or decrease ACEs and PREs. Directing the supply air away from the occupant will most likely reduce ACE and PRE. Changing the air supply temperature without recirculation of supply air (not an option with the current designs) might increase or decrease ACE or have no effect. Further research is also necessary to identify the best methods to maintain high values of ACE and PRE while enabling occupants to significantly change their thermal environment.

Overall, the results of this current set of experiments are very encouraging. The high values of ACE and PRE measured in this study suggest that these two desk-top TAC systems can be used to improve ventilation and pollutant removal at the breathing zone if normal rates of outside air supply are maintained. Alternately, energy savings could be realized while maintaining a typical level of IAQ at the breathing zone by allowing rates of outside air supply to be reduced. For example, the Design Ventilation Rate as recommended in ASHRAE Standard 62, may be corrected by using the air-change effectiveness. The corrected design ventilation rate is the ratio of the Design Ventilation Rate to the air-change effectiveness (ANSI/ASHRAE 129-1997). Thus, values of ACE from 1.3 to 1.9 would translate to a corrected design ventilation rate 23% to 47% less than the ASHRAE Standard 62 Design Ventilation Rate, assuming the airflow pattern is not significantly changed at the lower flow rates.

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Table 1. Experimental conditions and results.

				Conditions from TAC per (TAC unit)				Conditions from Overhead Ventilation System per (TAC unit)					Pollutant Removal Efficiencies	
TEST	Climadesk or PEM	Air Supply Direction	Manikin Position[2]	%OA	Supply Flow[3] (L/s)	OA Flow[3] (L/s)	Supply Temp (C)	%OA[4]	Supply Flow (L/s)	OA Flow[4] (L/s)	Room Temp (C)	Air Change Effectiveness[5]	Floor Source[6]	Body Source[7]
129 W	Climadesk	NA	Upright	100	7	7	19.3	0	35	0	24.1	1.05	0.95	0.98
130	Climadesk	Vertical	Upright	100	7	7	19.1	0	36	0	25.6	1.03	0.88	1.04
132	Climadesk	Vert & Horiz[1]	Upright	100	7	7	19.6	0	35	0	25.1	1.06	1.00	1.28
145	Climadesk	Vert & Horiz[1]	Upright	100	7	7	18.4	0	31	0	25.3	1.15	1.14	1.47
131	Climadesk	Horizontal[1]	Upright	100	7	7	20.2	0	35	0	25.9	1.37	1.15	1.35
140	Climadesk	Horizontal[1]	Upright	100	7	7	25.8	0	33	0	25.5	1.33	1.17	1.31
141	Climadesk	Vertical	Lean	100	7	7	19.4	0	31	0	25.1	1.73	1.55	1.44
142	Climadesk	Vertical	Lean	100	7	7	19.1	0	31	0	25.3	1.83	1.49	1.52
143	Climadesk	Vertical	Lean	100	3	3	24.4	12	31	4	25.6	1.75	1.38	1.52
144	Climadesk	Vertical	Lean	100	3	3	26.1	12	31	4	27.5	1.94	1.35	1.58
135	PEM	Parallel	Upright	21	37	8	19.2	0	17	0	22.9	NA	0.92	1.11
136	PEM	Parallel	Upright	19	38	7	19.1	0	30	0	22.7	NA	0.93	1.08
137	PEM	Parallel	Upright	20	38	8	19.3	0	31	0	23.8	1.04	0.98	1.09
133	PEM	Toward	Upright	100	10	10	19.7	0	33	0	24.8	1.63	1.25	1.54
139	PEM	Toward	Upright	100	9	9	19.6	0	34	0	24.3	1.42	1.20	1.46
134	PEM	Toward	Upright	100	10	10	19.5	0	34	0	24.2	NA	1.20	1.43
138	PEM	Toward	Upright	15	15	2	19.0	20	34	7	24.3	1.17	1.00	1.07

W. Air in chamber well mixed with oscillating desk fans.

1. Underdesk nozzles pointed
inward.
2. Upright: Manikin seated upright about 15 cm (6 inches) from edge of
desk.
   Lean: Nose of manikin in vertical jet from Climadesk.
3. Average flow of two operating TAC systems.
4. System set for 0% outside air, however some outside air leaked into the ventilation system.
5. Air Change Effectiveness = Age of Air in Return / Age of Air in Ventilated Breathing Zone.
6. Pollutant sources on the floor in each of four workstations.
7. Pollutant sources on the bodies of each manikin.

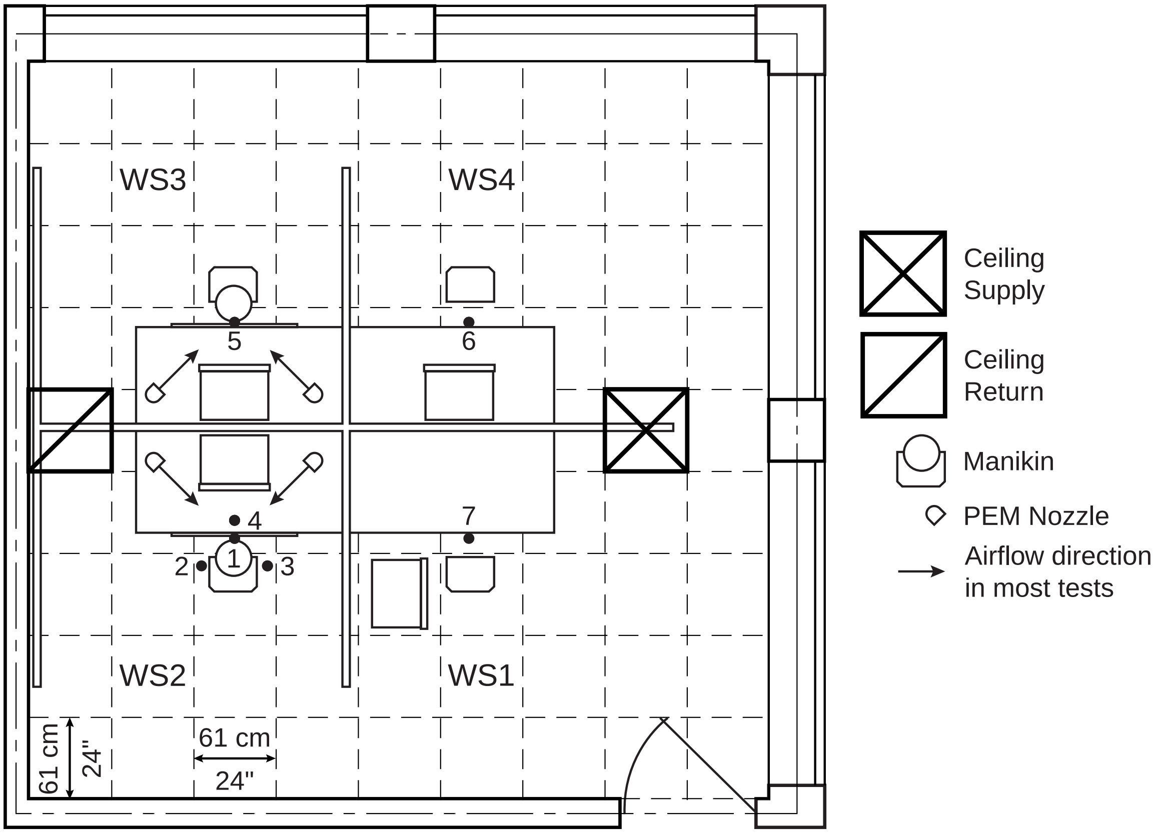

Figure 1. Plan view of CEC with workstations denoted WS1, WS2, WS3 and WS4. All sample points were 1.1 m above the floor. Points 1 and 5 are 3 cm below the tip of the nose; points 2 and 3 are immediately above each shoulder; point 4 is 15 cm in front of the nose; points 6 and 7 are at the edge of the desk.

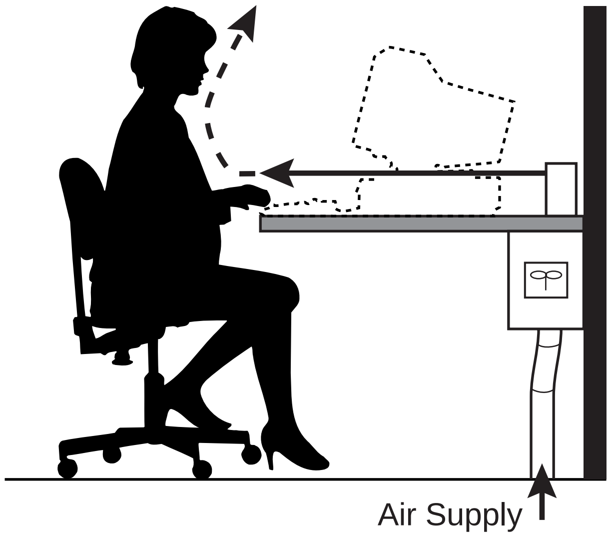

Figure 2. Air supply from the PEM (solid line) toward occupant, entrained in the thermal plume around occupant (dashed line).

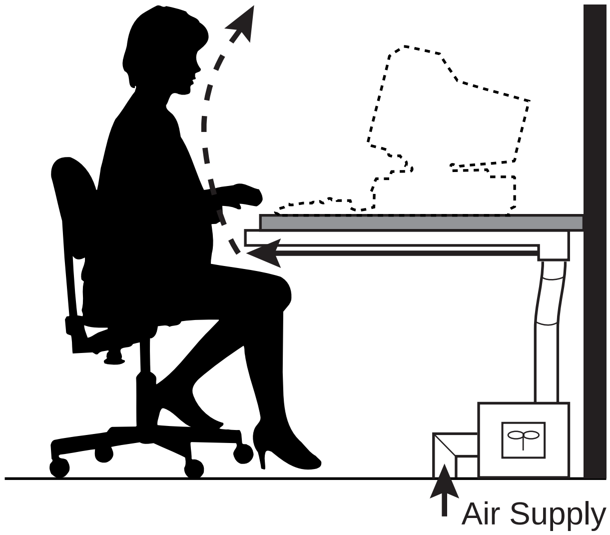

Figure 3. Air supplied horizontally from the Climadesk (solid line) toward occupant, entrained in the thermal plume around occupant (dashed line).

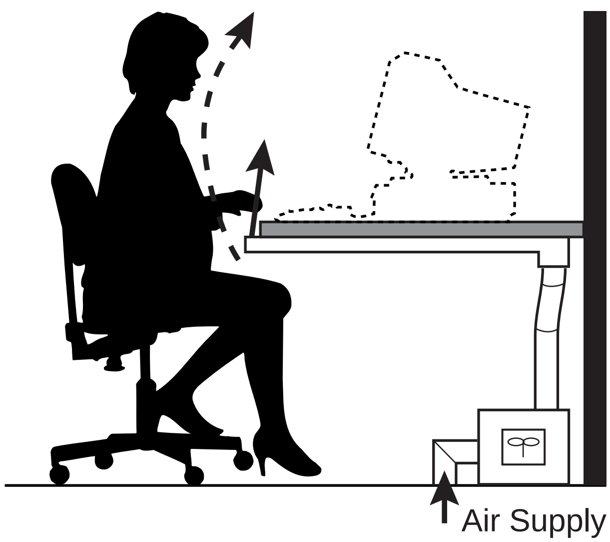

Figure 4. Air supplied vertically from the Climadesk (solid line) toward occupant, entrained in the thermal plume around occupant (dashed line).

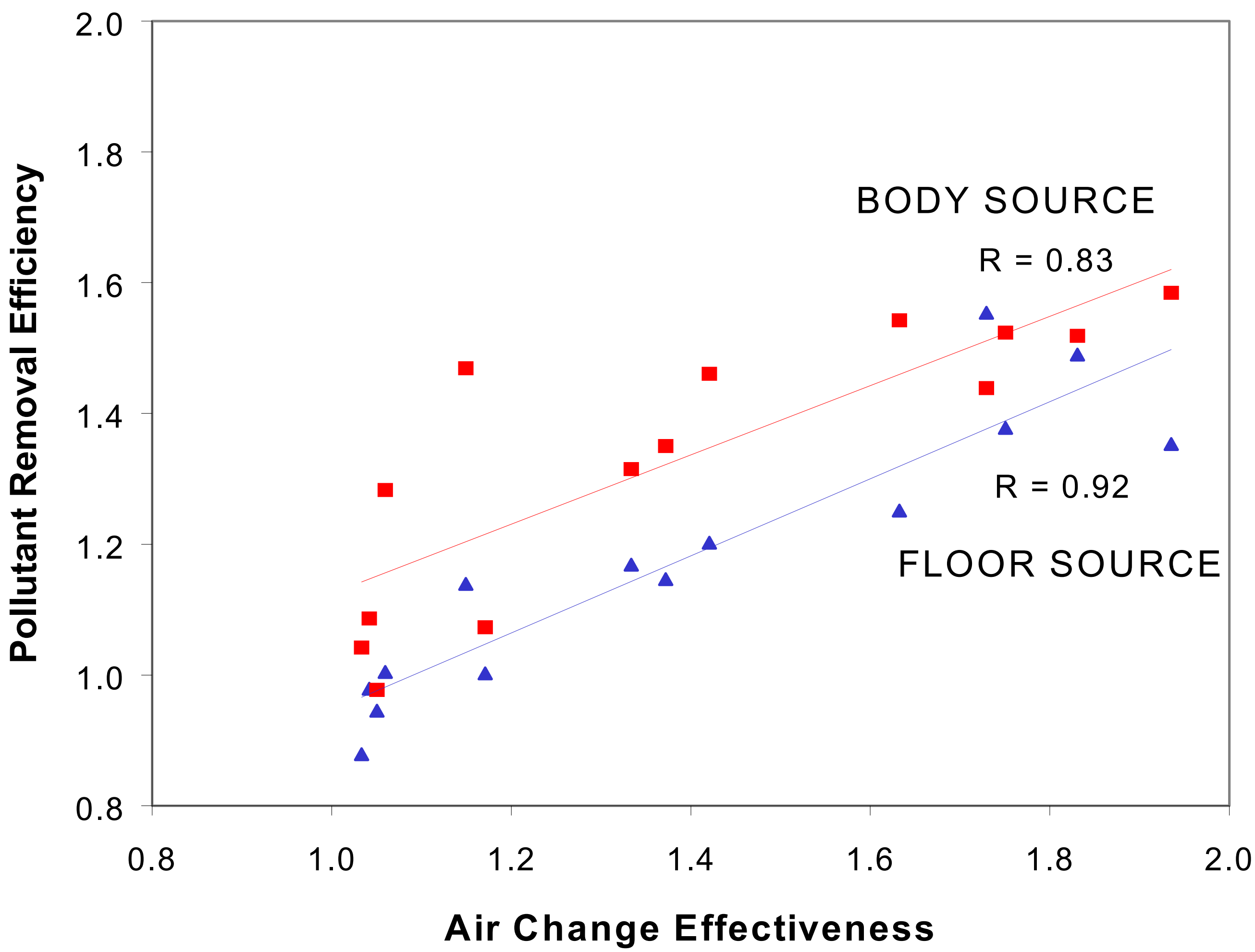

Figure 5. Pollutant Removal Efficiency versus Air Change Effectiveness for Body and Floor sources.